Sterile neutrino searches at future colliders

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NUFACT2017, Uppsala

September 28, 2017

One of the big open questions in BSM physics:

What is the origin of the observed neutrinos masses?

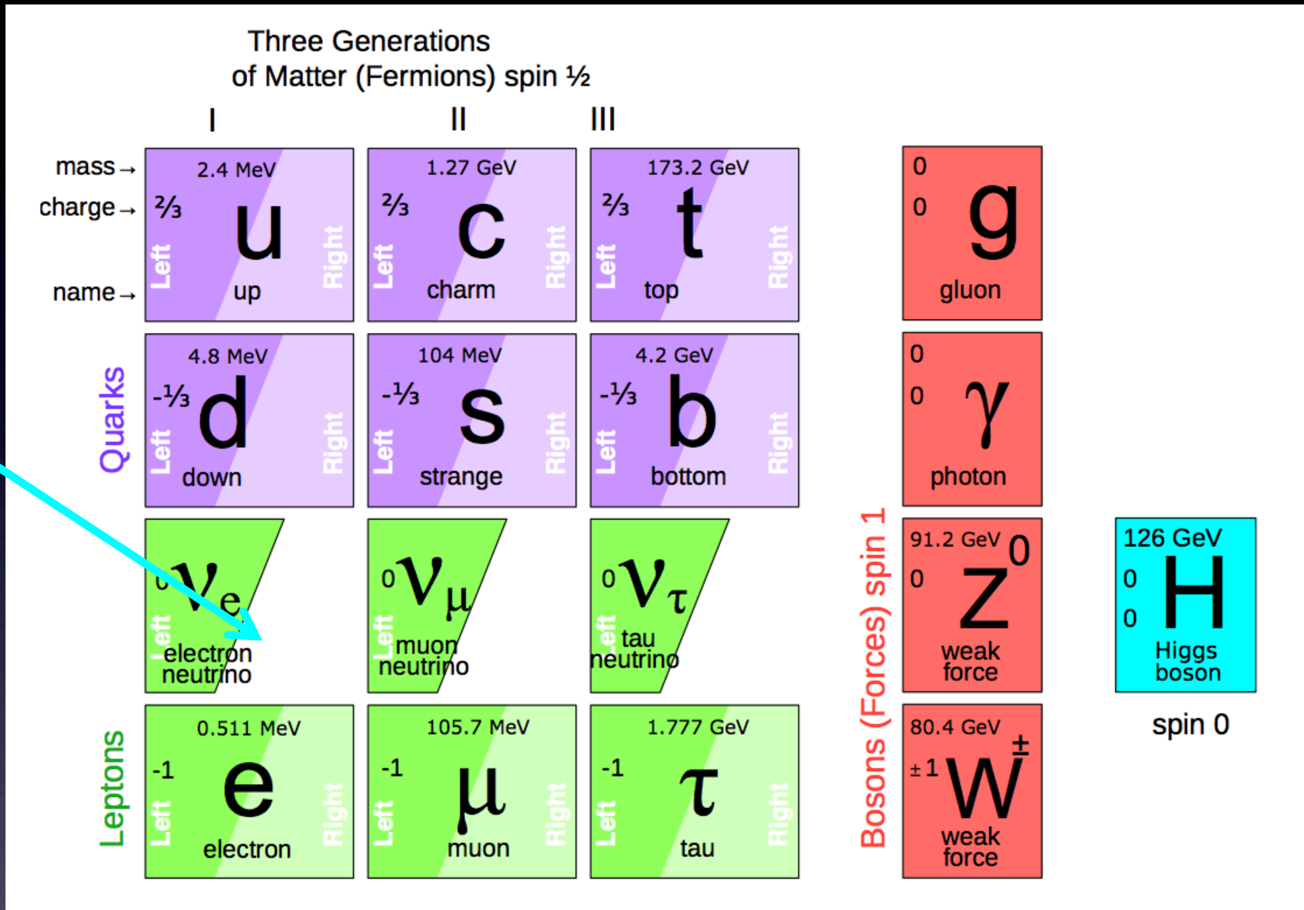
Outline

- Introduction: Some basics on sterile neutrinos
- Then: focus on EW scale sterile neutrinos. How can there be sterile neutrinos with mass $M \sim \Lambda_{EW}$ and “large” Yukawa couplings Y_ν?
- Which observable effects allow to test such models?
  - $M >> \Lambda_{EW}$: “Non-unitarity effects” (indirect tests)
  - $M \sim \Lambda_{EW}$: On-shell heavy neutrino effects (direct tests at colliders, various promising signature processes)
  - $M < m_W$: Very sensitive searches via “displaced vertices” at colliders
- Discovery prospects at possible future colliders (ee, ep and pp)

Sterile (= right-chiral) neutrinos?

There are no right-chiral neutrino states (ν_{Ri}) in the Standard Model

➔ ν_{Ri} would be completely neutral under all SM symmetries



Adding ν_{Ri} leads to the following extra terms in the Lagrangian density:

$$\mathscr{L} = \mathscr{L}_{\mathrm{SM}} - \frac{1}{2}\overline{\nu_{\mathrm{R}}^{I}} M_{IJ}^{N} \nu_{\mathrm{R}}^{cJ} - (Y_N)_{I\alpha} \overline{\nu_{\mathrm{R}}^{I}} \widetilde{\phi}^{\dagger} L^{\alpha} + \mathrm{H.c.}$$

M: sterile ν mass matrix

Y_N: neutrino Yukawa matrix (Dirac mass terms)

Light neutrino masses via the seesaw mechanism

Mass matrix of the (three) light neutrinos

Mass matrix of the (2+n) sterile (= right-handed) neutrinos (masses of Majorana-type)

$$(m_\nu)_{\alpha\beta} = -\frac{v_{EW}^2}{2}\left(Y_\nu^T \cdot M^{-1} \cdot Y_\nu\right)_{\alpha\beta}$$

Valid for $v_{EW}\, y_\nu << M_R$

„Seesaw Formula"

Neutrino Yukawa matrix

P. Minkowski ('77), Mohapatra, Senjanovic, Yanagida, Gell-Mann, Ramond, Slansky, Schechter, Valle, …

From neutrino oscillation experiments and mass searches:

$|m_3^2 - m_1^2| \approx 2.4 \cdot 10^{-3}\, eV^2$

$m_2^2 - m_1^2 \approx 7.5 \cdot 10^{-5}\, eV^2$

all three m_i below ~ 0.2 eV

+ measurements of the leptonic mixing angles (from neutrino osc. experiments)

Note: At least two sterile neutrinos are required
➔ generate masses for two of the light neutrinos
(necessary for realizing the two observed mass splittings)

What do the measured light neutrino parameters tell us about the sterile neutrino parameters M, Y_ν?

What do we know about the neutrino parameters?

Getting started: 1 ν_R, 1 ν_L

$$\Rightarrow \quad m_\nu = \frac{1}{2} \frac{v_{EW}^2 |y_\nu|^2}{M_R}$$

➔ Knowledge of m_ν implies relation between y_ν and M_R

“Naive” seesaw relation: $y_\nu^2 < O(10^{-13})$ (M / 100 GeV)

What do we know about the sterile neutrino parameters?

Example 1: **2 ν_R, 2 ν_L**

Example of a small perturbation

$$Y_\nu = \begin{pmatrix} \mathcal{O}(y_\nu) & 0 \\ 0 & \mathcal{O}(y_\nu) \end{pmatrix}, \quad M = \begin{pmatrix} M_R & 0 \\ 0 & M_R + \varepsilon \end{pmatrix}$$

$$\Rightarrow \quad m_{\nu_i} = \frac{v_{EW}^2 \, \mathcal{O}(y_\nu^2)}{M_R} \left(1 + \varepsilon \, \delta_{i2}\right)$$

➔ Also in this example: Knowledge of $m_{\nu i}$ implies relation between $y_{\nu i}$ and M_R

What do we know about the sterile neutrino parameters?

Example 2: 2 ν_R, 2 ν_L

Similar: “inverse” seesaw, “linear” seesaw

See e.g.: D. Wyler, L. Wolfenstein ('83), R. N. Mohapatra, J. W. F. Valle ('86), M. Shaposhnikov (,07), J. Kersten, A. Y. Smirnov ('07), M. B. Gavela, T. Hambye, D. Hernandez, P. Hernandez ('09), M. Malinsky, J. C. Romao, J. W. F. Valle ('05), ⋯

$$Y_\nu = \begin{pmatrix} \mathcal{O}(y_\nu) & 0 \\ \mathcal{O}(y_\nu) & 0 \end{pmatrix}, \quad M = \begin{pmatrix} 0 & M_R \\ M_R & \varepsilon \end{pmatrix}$$

Example of a small perturbation

$$\Rightarrow \quad m_\nu = 0 + \varepsilon \, \frac{v_{EW}^2 \, \mathcal{O}(y_\nu^2)}{M_R^2}$$

➔ **In general: No “fixed relation” between y_ν and M_R, larger y_ν possible!**

What do we know about the sterile neutrino parameters?

Example 2: 2 ν_R, 2 ν_L

Similar: "inverse" seesaw, "linear" seesaw

$$Y_\nu = \begin{pmatrix} \mathcal{O}(y_\nu) & 0 \\ \mathcal{O}(y_\nu) & 0 \end{pmatrix}, \quad M = \begin{pmatrix} 0 & M_R \\ M_R & \varepsilon \end{pmatrix}$$

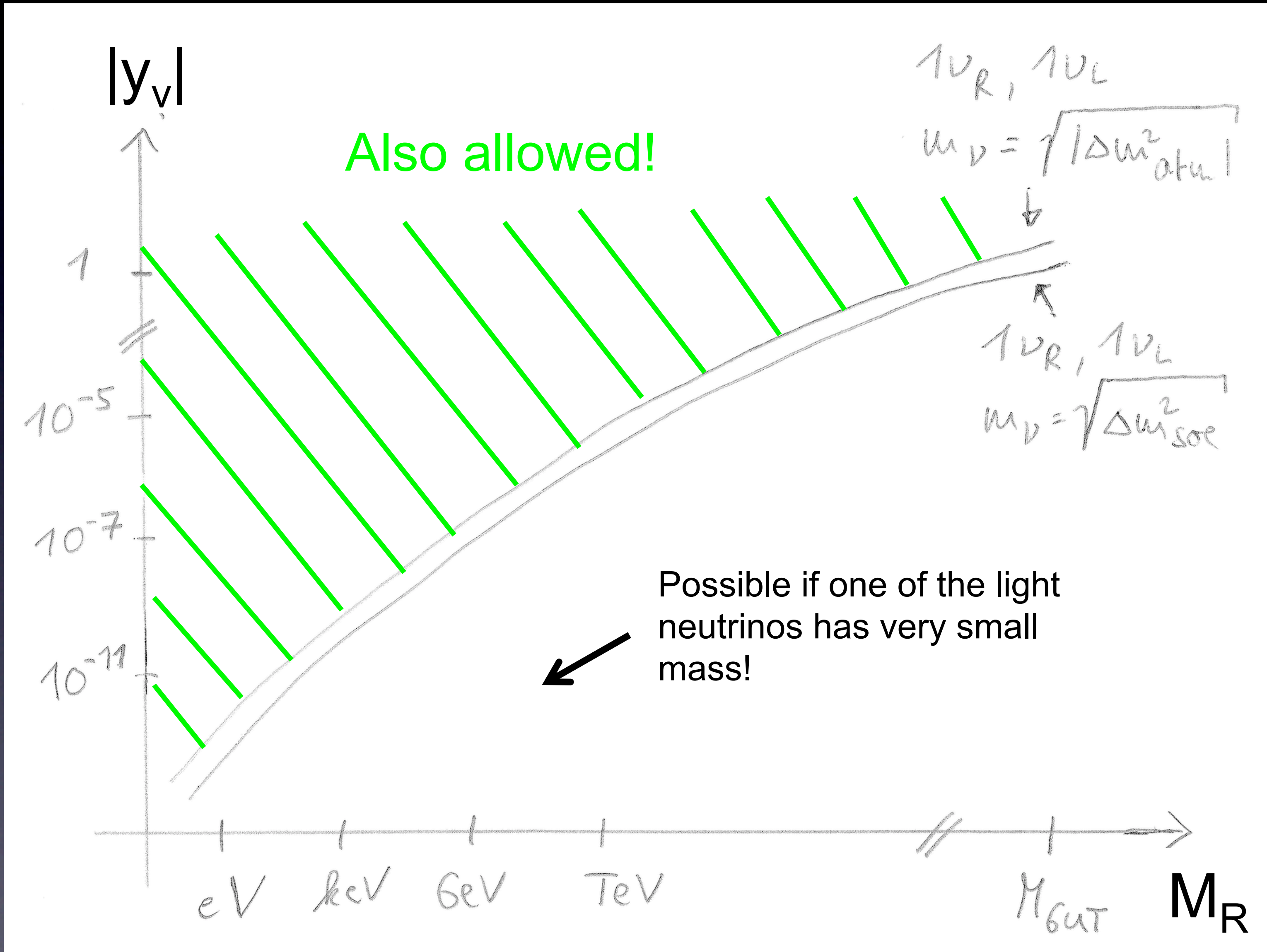
$$\Rightarrow \quad m_\nu = 0 + \varepsilon \, \frac{v_{EW}^2 \, \mathcal{O}(y_\nu^2)}{M_R^2}$$

Example for "protective" symmetry:

	L_α	ν_{R1}	ν_{R2}
Lepton-#	**+1**	**+1**	**-1**

Note: Can be realized by symmetries, e.g. by an (approximate) "lepton number"-like symmetry

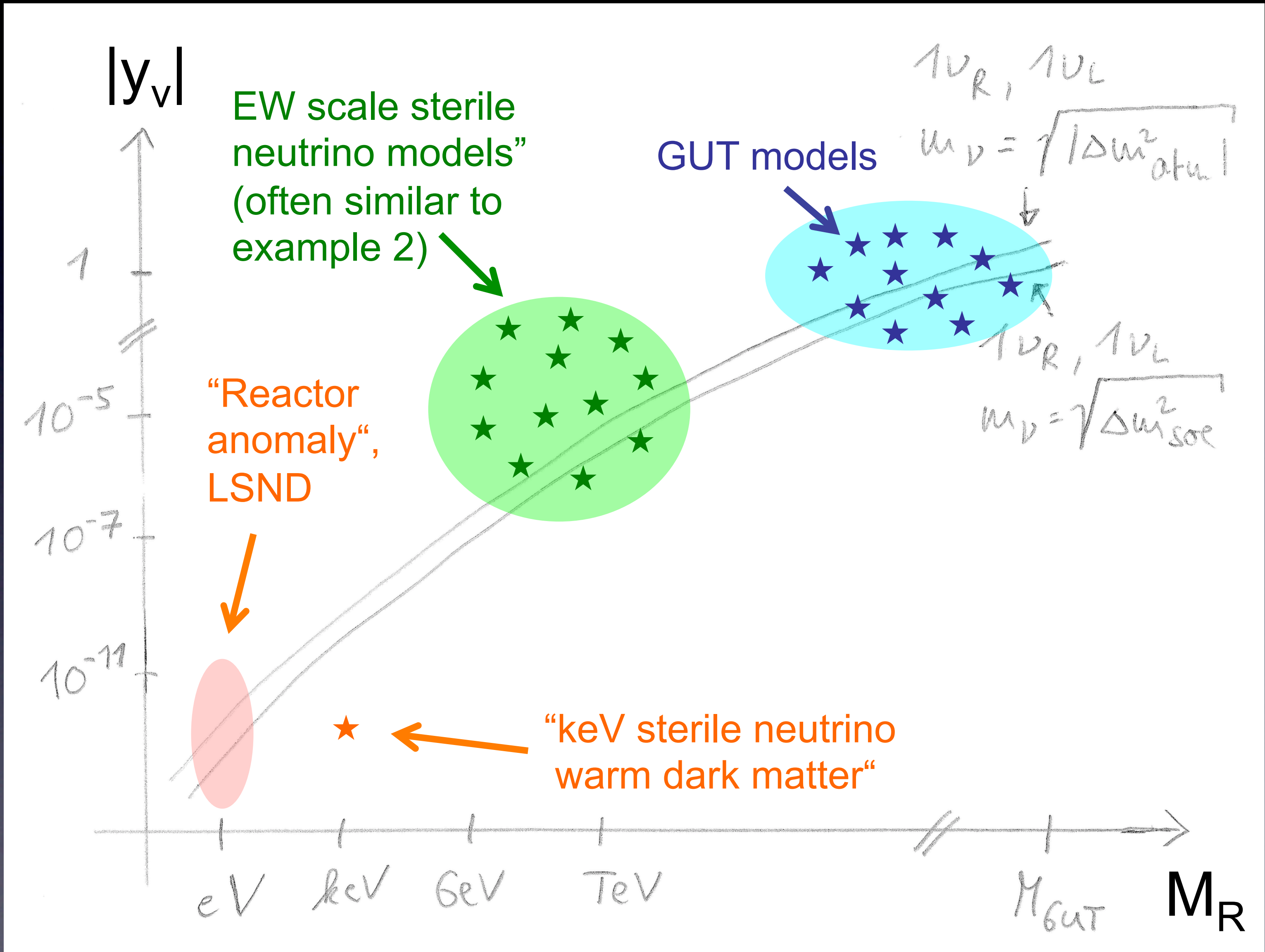
Possible values of M_R and y_ν



Not considering experimental constraints

"Landscape" of sterile neutrino models

Examples, schematic



Not considering experimental constraints

A benchmark model for EW scale sterile ν:
SPSS (Symmetry Protected Seesaw Scenario)

Consider 2+n sterile neutrinos (plus the three active) ➔ with M and Y_ν for two of the steriles as in example 2 due to some generic “lepton number”-like symmetry)

$$Y_\nu = \begin{pmatrix} y_{\nu_e} & 0 \\ y_{\nu_\mu} & 0 \\ y_{\nu_\tau} & 0 \end{pmatrix}, \quad M = \left(\begin{array}{cc|ccc} 0 & M_R & & 0 & \\ M_R & 0 & & & \\ \hline & & * & * & \cdots \\ & 0 & * & * & \\ & & \vdots & & \ddots \end{array}\right)$$

+ O(ε) perturbations to generate the light neutrino masss (which we can often neglect for collider studies)

Similar: “inverse” seesaw, “linear” seesaw

Additional sterile neutrinos can exist, but have no effects at colliders (which can be realised easily, e.g. by giving lepton number = 0 to them).

For details on the SPSS, see:
S.A., O. Fischer (arXiv:1502.05915)

A benchmark model fo…

SPSS (Symmetry Prote…

Note: Since in the SPSS we allow for additional sterile neutrinos, M and y_α (α=e,μ,τ) are indeed free parameters (not constrained by m_ν). In specific models there are correlations among the y_α. Strategy of the SPSS: study how to measure the y_α independently, in order to test (not a priori assume) such correlations!

Consider 2+n sterile neutrinos (plus the th… the steriles as in example 2 due to some …

$$Y_\nu = \begin{pmatrix} y_{\nu_e} & 0 \\ y_{\nu_\mu} & 0 \\ y_{\nu_\tau} & 0 \end{pmatrix}, \quad M = \begin{pmatrix} \begin{matrix} 0 & M_R \\ M_R & 0 \end{matrix} & 0 \\ 0 & \begin{matrix} * & * & \cdots \\ * & * & \ddots \\ \vdots & & \end{matrix} \end{pmatrix}$$

+ O(ε) perturbations to generate the light neutrino masss (which we can often neglect for collider studies)

Additional sterile neutrinos can exist, but have no effects at colliders (which can be realised easily, e.g. by giving lepton number = 0 to them).

Similar: “inverse” seesaw, “linear” seesaw

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Testing specific low scale seesaw models: Examples

A benchmark model f
SPSS (Symmetry Prote

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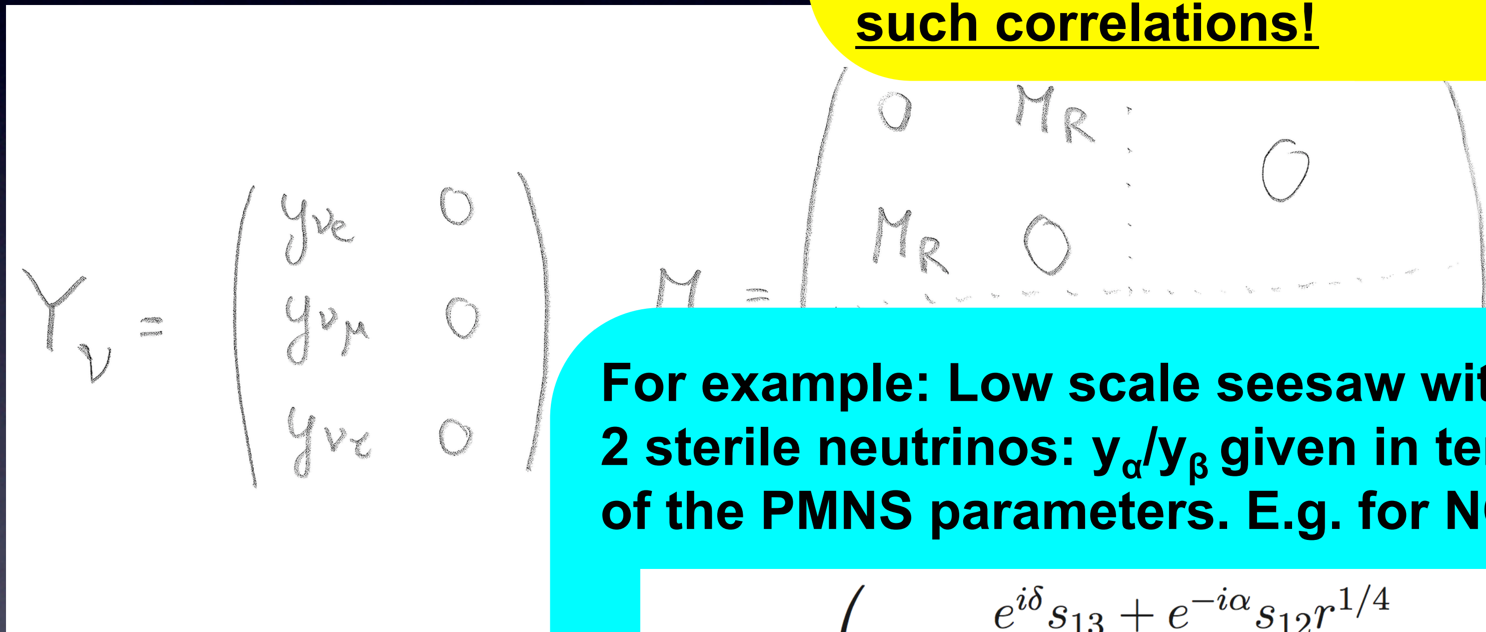


+ O(ε)
perturbations
to generate the
...utrino

...we can
...eglect for
... studies)

For example: Low scale seesaw with 2 sterile neutrinos: y_α/y_β given in tems of the PMNS parameters. E.g. for NO:

$$Y_N^T \simeq y \begin{pmatrix} e^{i\delta} s_{13} + e^{-i\alpha} s_{12} r^{1/4} \\ s_{23}\left(1 - \frac{\sqrt{r}}{2}\right) + e^{-i\alpha} r^{1/4} c_{12} c_{23} \\ c_{23}\left(1 - \frac{\sqrt{r}}{2}\right) - e^{-i\alpha} r^{1/4} c_{12} s_{23} \end{pmatrix}$$

Cf.: Gavela, Hambye, D. Hernandez, P. Hernandez ('09)

For details on the SPSS, see:
S.A., O. Fischer (arXiv:1502.05915)

Further predictions in specific types of low scale seesaw mechanisms: ΔM of heavy ν's

*) Basis: (ν_L^α, N_1, N_2)

Perturbations of the mass matrix:* $M_\nu = \begin{pmatrix} 0 & m_D & \varepsilon_{\rm lin} \\ (m_D)^T & \tilde{\varepsilon} & M \\ \varepsilon_{\rm lin}^T & M & \varepsilon_{\rm inv} \end{pmatrix}$

$\varepsilon_{\rm lin}$ linear seesaw

$\varepsilon_{\rm inv}$ inverse seesaw

($\tilde{\varepsilon}$ additional parameter, no contribution to light neutrino masses)

Perturbations O(ε) generate the light neutrino masses and, e.g. in the case of the minimal linear seesaw model, lead to a **prediction for the heavy neutrino mass splitting ΔM** (**in terms of the light neutrino mass splittings**):

$$\Delta M^{\rm lin,NO} = \frac{2\rho_{\rm NO}}{1-\rho_{\rm NO}} \sqrt{\Delta m^2_{21}} = 0.0416\,{\rm eV}$$

$$\Delta M^{\rm lin,IO} = \frac{2\rho_{\rm IO}}{1+\rho_{\rm IO}} \sqrt{\Delta m^2_{23}} = 0.000753\,{\rm eV}$$

$$\rho_{\rm NO} = \frac{\sqrt{r+1}-\sqrt{r}}{\sqrt{r}+\sqrt{r+1}} \text{ and } r = \frac{|\Delta m^2_{21}|}{|\Delta m^2_{32}|}$$

$$\rho_{\rm IO} = \frac{\sqrt{r+1}-1}{\sqrt{r+1}+1} \text{ and } r = \frac{|\Delta m^2_{21}|}{|\Delta m^2_{13}|}$$

Cf.: S.A., E. Cazzato, O. Fischer (arXiv:1709.03797)

... More about this later in my talk!

What are the observable effects of EW scale sterile neutrinos?

(This part we neglect the O(ε) effects; will be discussed later ...)

We consider the SPSS: Instead of the y_α, we use the active sterile mixing angles θ_α, (α=e,μ,τ)

In the symmetry limit:

$$\mathscr{L}_N = - \overline{N_R}^1 M N_R^{c\,2} - y_\alpha \overline{N_R}^1 \widetilde{\phi}^\dagger L^\alpha + \text{H.c.}$$
$$+ \ldots \text{ (terms from additional sterile νs)}$$

- The leptonic mixing matrix to leading order in the active-sterile mixing parameters:

$$U_{5x5} = \begin{pmatrix} \mathcal{N}_{1e} & \mathcal{N}_{1\mu} & \mathcal{N}_{1\tau} & -\frac{\mathrm{i}}{\sqrt{2}}\theta_e & \frac{1}{\sqrt{2}}\theta_e \\ \mathcal{N}_{2e} & \mathcal{N}_{2\mu} & \mathcal{N}_{2\tau} & -\frac{\mathrm{i}}{\sqrt{2}}\theta_\mu & \frac{1}{\sqrt{2}}\theta_\mu \\ \mathcal{N}_{3e} & \mathcal{N}_{3\mu} & \mathcal{N}_{3\tau} & -\frac{\mathrm{i}}{\sqrt{2}}\theta_\tau & \frac{1}{\sqrt{2}}\theta_\tau \\ 0 & 0 & 0 & \frac{\mathrm{i}}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ -\theta_e^* & -\theta_\mu^* & -\theta_\tau^* & \frac{-\mathrm{i}}{\sqrt{2}}(1-\frac{1}{2}\theta^2) & \frac{1}{\sqrt{2}}(1-\frac{1}{2}\theta^2) \end{pmatrix}$$

- Active-sterile neutrino mixing parameters:

$$\theta_\alpha = \frac{y_\alpha^*}{\sqrt{2}} \frac{v_{\mathrm{EW}}}{M}, \qquad \alpha = e, \mu, \tau$$

Parameters:
M, y_α, (α=e,μ,τ)
or equivalently
M, θ_α, (α=e,μ,τ)

Observable effects of the sterile neutrinos: M >> Λ_{EW}

(Effective) mixing matrix of light neutrinos is a submatrix of a larger unitary mixing matrix (mixing with additional heavy particles)

Main effect for M >> Λ_{EW}:
"Leptonic non-unitary"

Langacker, London ('88); S.A., Biggio, Fernandez-Martinez, Gavela, Lopez-Pavon ('06), ⋯
Gives rise to NSIs at source, detector & with matter: see e.g. S.A., Baumann, Fernandez-Martinez (arXiv:0807.1003)
Global constraints on $\varepsilon_{\alpha\beta}$: S.A., Fischer (arXiv:1407.6607)

$$U = \begin{pmatrix} \mathcal{N}_{1e} & \mathcal{N}_{1\mu} & \mathcal{N}_{1\tau} & -\frac{\mathrm{i}}{\sqrt{2}}\theta_e & \frac{1}{\sqrt{2}}\theta_e \\ \mathcal{N}_{2e} & \mathcal{N}_{2\mu} & \mathcal{N}_{2\tau} & -\frac{\mathrm{i}}{\sqrt{2}}\theta_\mu & \frac{1}{\sqrt{2}}\theta_\mu \\ \mathcal{N}_{3e} & \mathcal{N}_{3\mu} & \mathcal{N}_{3\tau} & -\frac{\mathrm{i}}{\sqrt{2}}\theta_\tau & \frac{1}{\sqrt{2}}\theta_\tau \\ 0 & 0 & 0 & \frac{\mathrm{i}}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ -\theta_e^* & -\theta_\mu^* & -\theta_\tau^* & \frac{-\mathrm{i}}{\sqrt{2}}(1-\frac{1}{2}\theta^2) & \frac{1}{\sqrt{2}}(1-\frac{1}{2}\theta^2) \end{pmatrix}$$

Non-unitarity parameters:

$$(NN^\dagger)_{\alpha\beta} = (1_{\alpha\beta} + \varepsilon_{\alpha\beta})$$

⇒ U_{PMNS} ≡ N is non-unitary

⇒ various obs. effects!

Relation to the parameters of the SPSS benchmark model

	y_{ν_α}	θ_α	$\varepsilon_{\alpha\beta}$
$y_{\nu_\alpha} =$	$-$	$\frac{\sqrt{2}M}{v_{\rm EW}}\theta_\alpha^*$	$-\frac{\sqrt{2}M}{v_{\rm EW}}\varepsilon_{\beta\alpha}/\sqrt{-\varepsilon_{\beta\beta}}$
$\theta_\alpha =$	$\frac{v_{\rm EW}}{\sqrt{2}M}y_{\nu_\alpha}^*$	$-$	$-\varepsilon_{\beta\alpha}/\sqrt{-\varepsilon_{\beta\beta}}$
$\varepsilon_{\alpha\beta} =$	$-\frac{v_{\rm EW}^2 y_{\nu_\alpha}^* y_{\nu_\beta}}{2M^2}$	$-\theta_\alpha^*\theta_\beta$	$-$

Non-unitarity parameters

Active-sterile neutrino mixing

Observable effects of the sterile neutrinos: $M \cong \Lambda_{EW}$

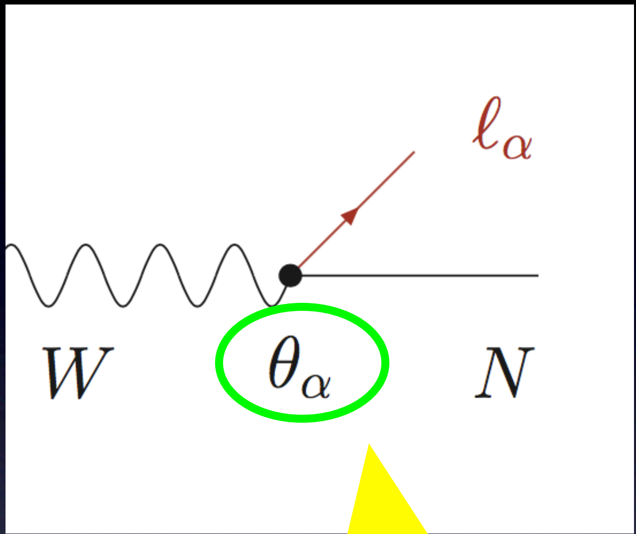
In addition for $M \cong \Lambda_{EW}$: Effects from on-shell heavy neutrinos

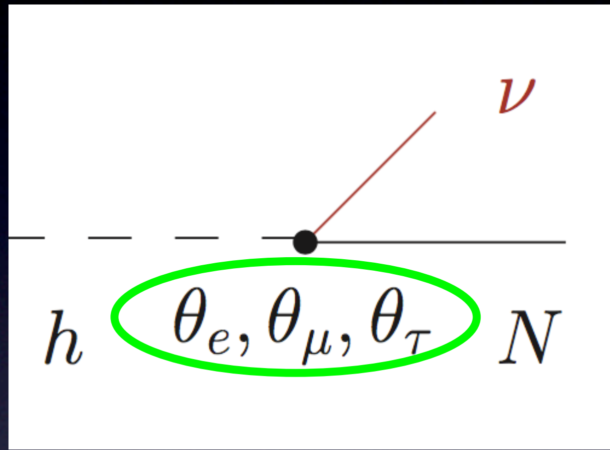
Sterile neutrinos mix with the active ones ➔ the heavy neutrinos (= mass eigenstates) participate in weak interactions!

$$U = \begin{pmatrix} \mathcal{N}_{1e} & \mathcal{N}_{1\mu} & \mathcal{N}_{1\tau} & -\frac{\mathrm{i}}{\sqrt{2}}\theta_e & \frac{1}{\sqrt{2}}\theta_e \\ \mathcal{N}_{2e} & \mathcal{N}_{2\mu} & \mathcal{N}_{2\tau} & -\frac{\mathrm{i}}{\sqrt{2}}\theta_\mu & \frac{1}{\sqrt{2}}\theta_\mu \\ \mathcal{N}_{3e} & \mathcal{N}_{3\mu} & \mathcal{N}_{3\tau} & -\frac{\mathrm{i}}{\sqrt{2}}\theta_\tau & \frac{1}{\sqrt{2}}\theta_\tau \\ 0 & 0 & 0 & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ -\theta_e^* & -\theta_\mu^* & -\theta_\tau^* & \frac{-\mathrm{i}}{\sqrt{2}}(1-\frac{1}{2}\theta^2) & \frac{1}{\sqrt{2}}(1-\frac{1}{2}\theta^2) \end{pmatrix}$$

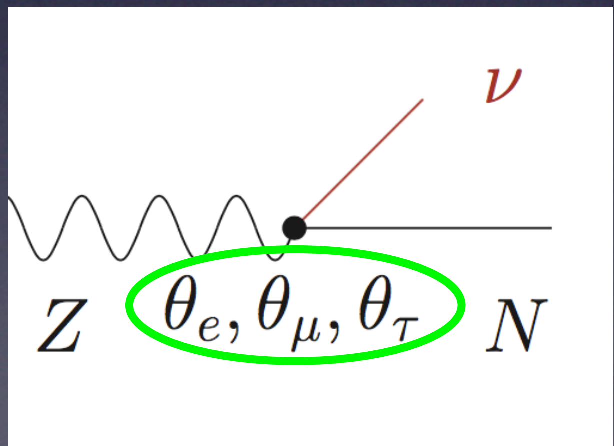
⇒ heavy neutrinos can get produced also in weak interaction processes!

Heavy neutrino interactions

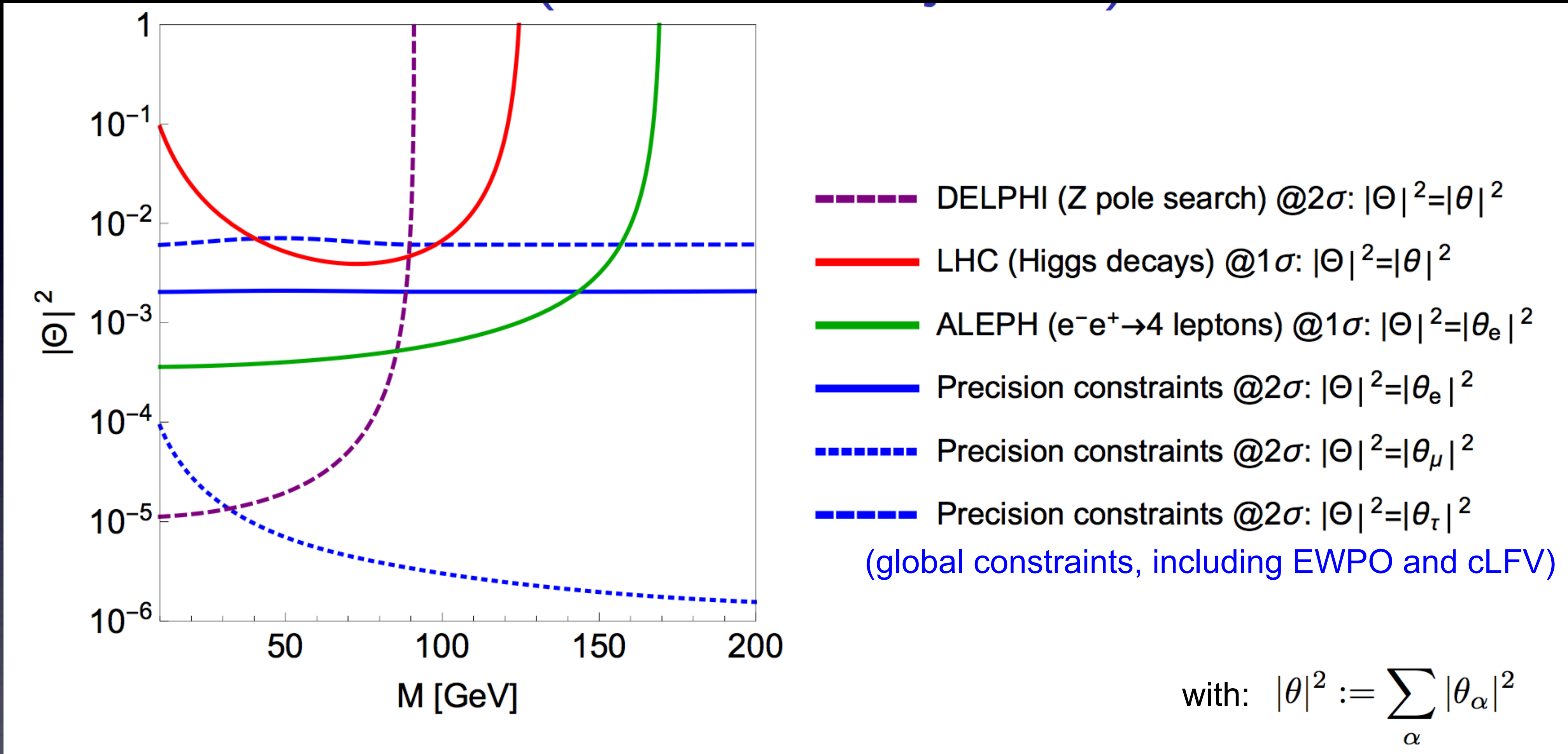




When W bosons are involved, there is a possible sensitivity to the flavour-dependent θ_α



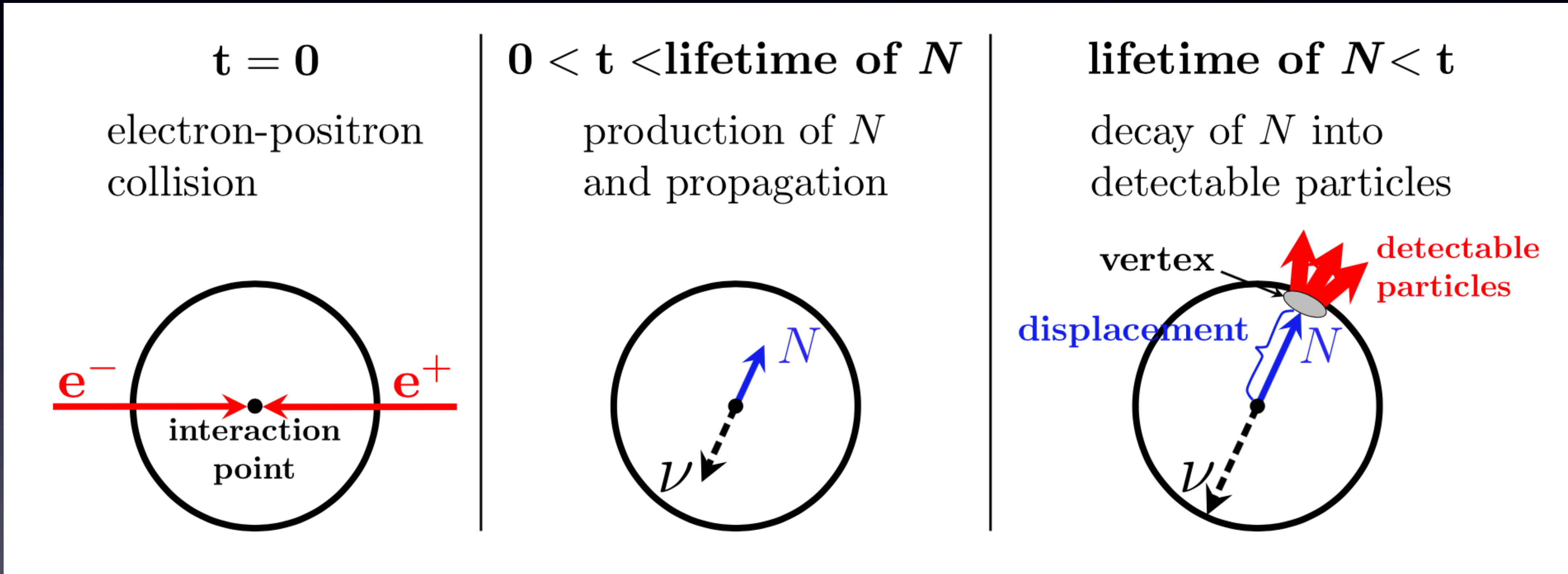
Present constraints on sterile neutrino parameters (conv. searches, M>10 GeV)



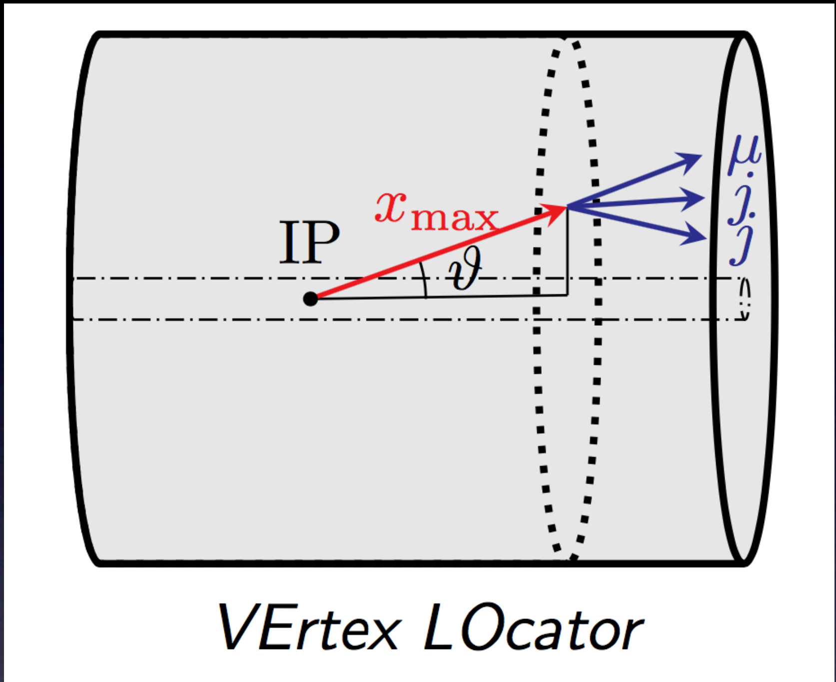
Constraints from present data (M > 10 GeV): S.A., O. Fischer (arXiv:1502.05915)
For a similar study, see also: E. Fernandez-Martinez, J .Hernandez-Garcia, J. Lopez-Pavon (arXiv:1605.08774)
Constraints for smaller M, see e.g.: M. Drewes, B. Garbrecht (arXiv:1502.00477)

Very sensitive searches possible for $M<m_W$ via "displaced vertices"

E.g. at an e^+e^- collider:



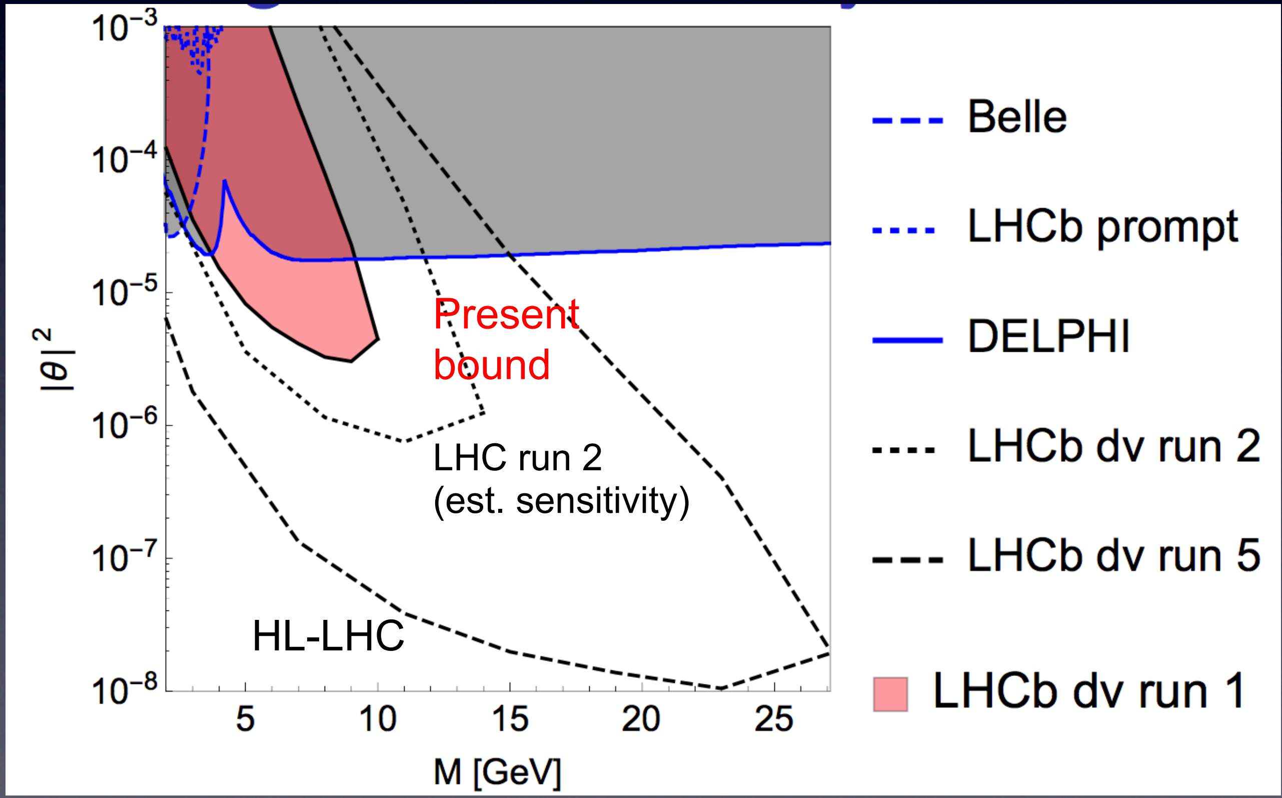
Present bounds (& estim. future sensitivities) from displaced vertex searches at LHCb



LHCb analysis exists for LHC run 1 data:

LHCb Collaboration, Eur. Phys. J. C 77 (2017) no.4, 224 arXiv:1612.00945

The results can be translated into bounds on $|\theta|^2$ (here for $\theta_e = \theta_\tau = 0$):



S. A., E. Cazzato, O. Fischer; arXiv:1706.05990

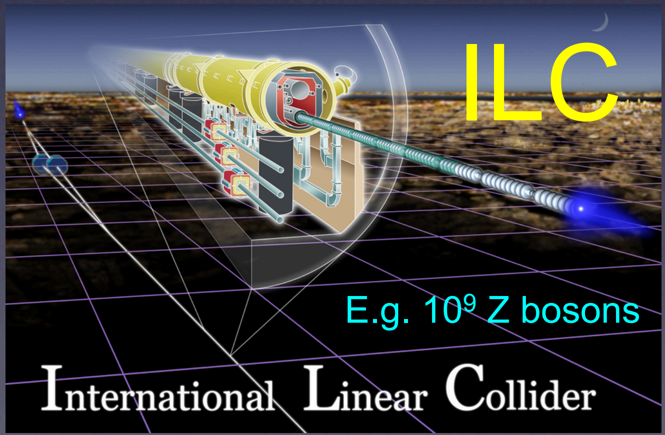
Remark: Forecasts for the sensitivities at Atlas and CMS for the HL-LHC phase are comparable, cf.:
E. Izaguirre, B. Shuve (2015)

What are the prospects for discovering sterile neutrinos at future collider experiments?

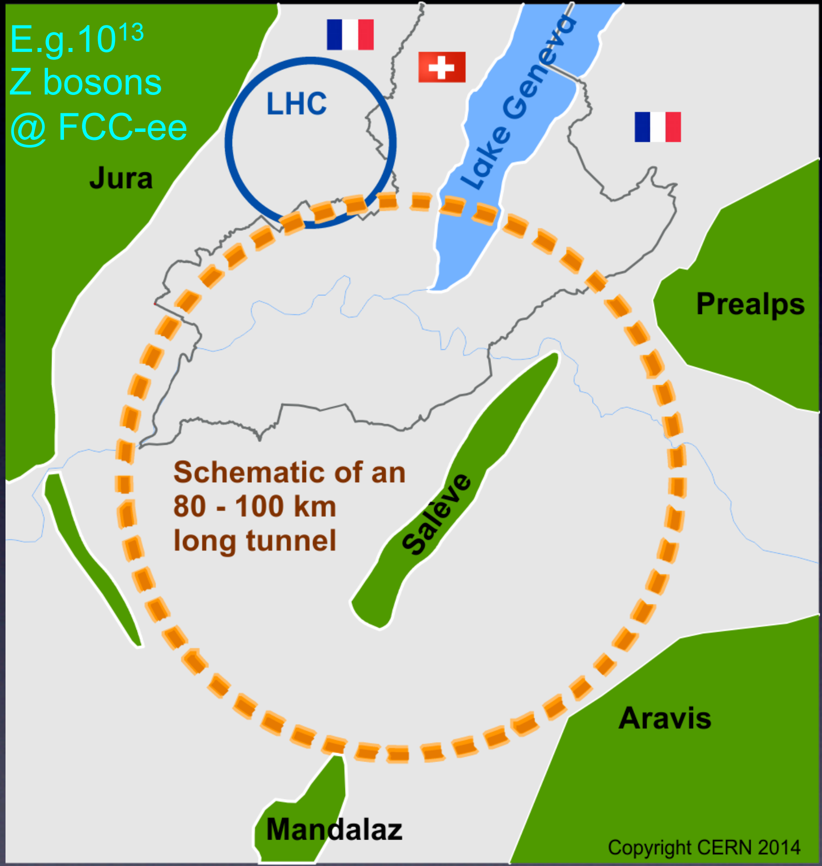
Note: I will consider the SPSS as a benchmark and restrict myself to M > 10 GeV

Ambitious plans for future colliders …

plans for circular collider in China

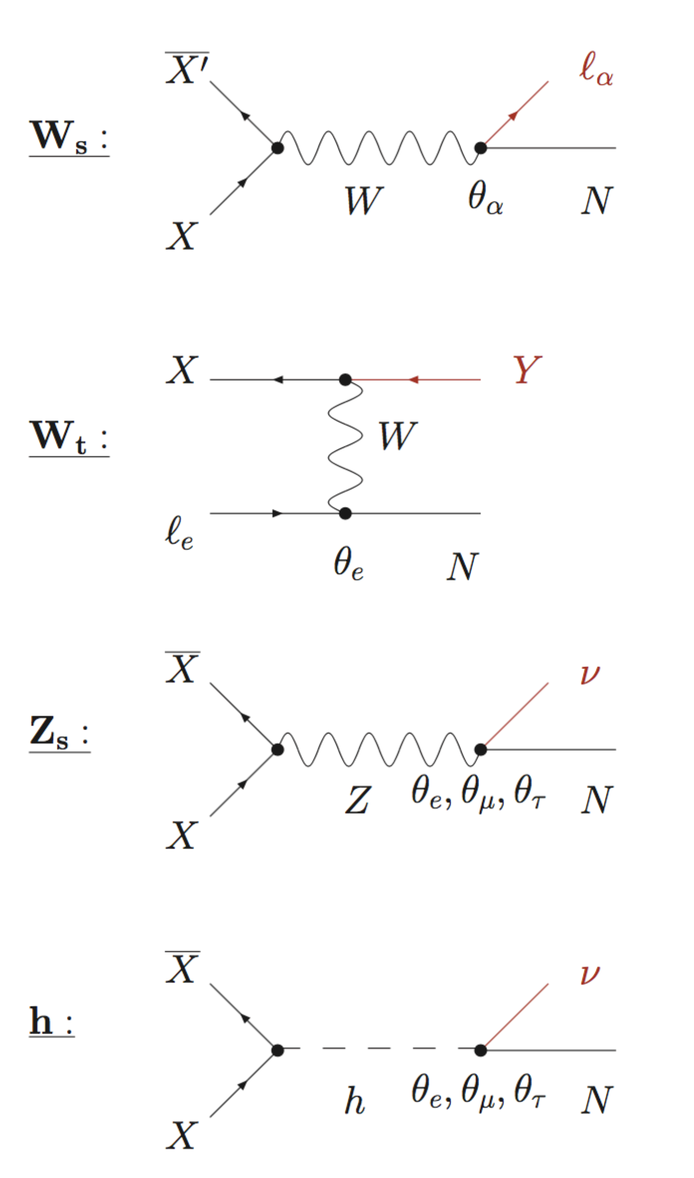


FCC (-ee, -hh, -eh)



FCC and CEPC may be operated with e^+-e^- (in first stage) → Z,W,h factory

Systematic assessment of signatures of sterile neutrinos at colliders



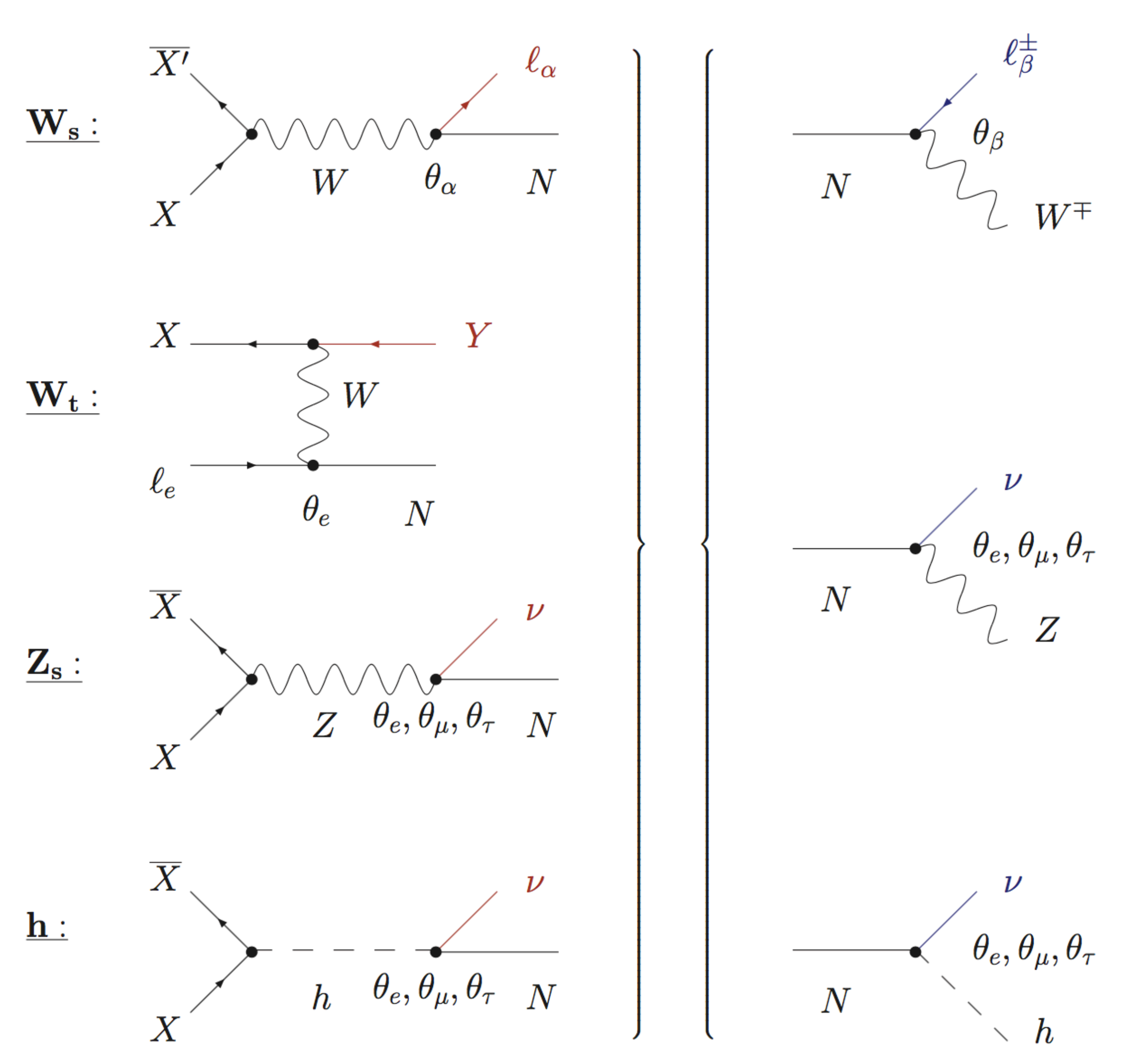
S.A., E. Cazzato, O. Fischer (arXiv:1612.02728)

Different collider types feature different production channels ···

	e^-e^+	pp	e^-p
$\mathbf{W_s}$	$\times$	✓+LNV/LFV	$\times$
$\mathbf{W_t}$	✓	$\times$	✓ +LNV/LFV
$\mathbf{Z_s}$	✓	✓	$\times$
$\mathbf{h}$	(✓)	(✓)	(✓)

Systematic assessment of signatures of sterile neutrinos at colliders

(at LO)

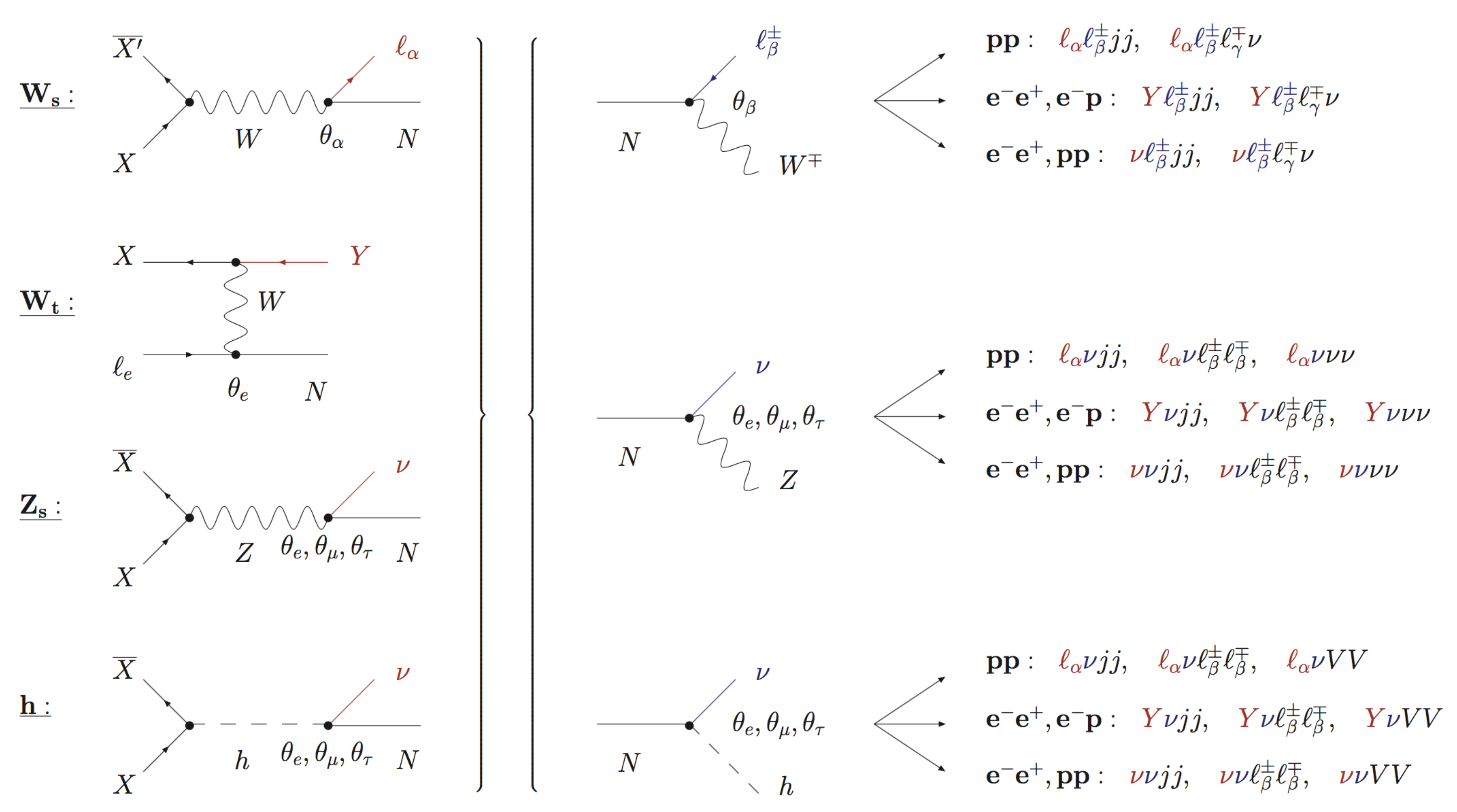


… and, including the different decay channels, sensitivity to different combinations of active-sterile mixing parameters:

		Decay channel	
		W	$Z(h)$
Production channel	$\mathbf{W_s}$	$\frac{\lvert\theta_\alpha\theta_\beta\rvert^2}{\lvert\theta\rvert^2}$	$\lvert\theta_\alpha\rvert^2$
	$\mathbf{W_t}$	$\frac{\lvert\theta_e\theta_\beta\rvert^2}{\lvert\theta\rvert^2}$	$\lvert\theta_e\rvert^2$
	$\mathbf{Z_s(h)}$	$\lvert\theta_\beta\rvert^2$	$\lvert\theta\rvert^2$

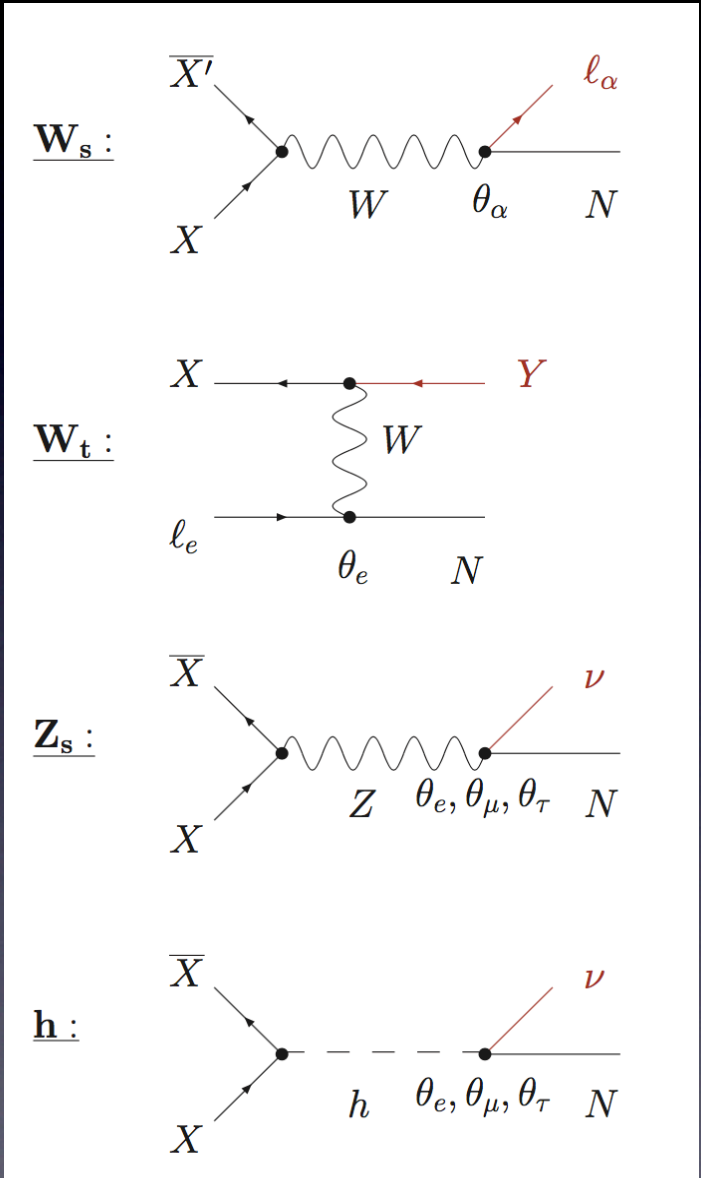
Systematic assessment of signatures of sterile neutrinos at colliders

(at LO)



Signatures with lepton flavour violation

(at LO)



Different collider types feature different production channels:

	e^-e^+	pp	e^-p
$\mathbf{W_s}$	×	✓+LNV/LFV	×
$\mathbf{W_t}$	✓	×	✓ +LNV/LFV
$\mathbf{Z_s}$	✓	✓	×
$\mathbf{h}$	(✓)	(✓)	(✓)

Lepton flavour violating LFV (and lepton number conserving LNC) signatures possible (with no SM background at parton level*). Very promising for future searches!

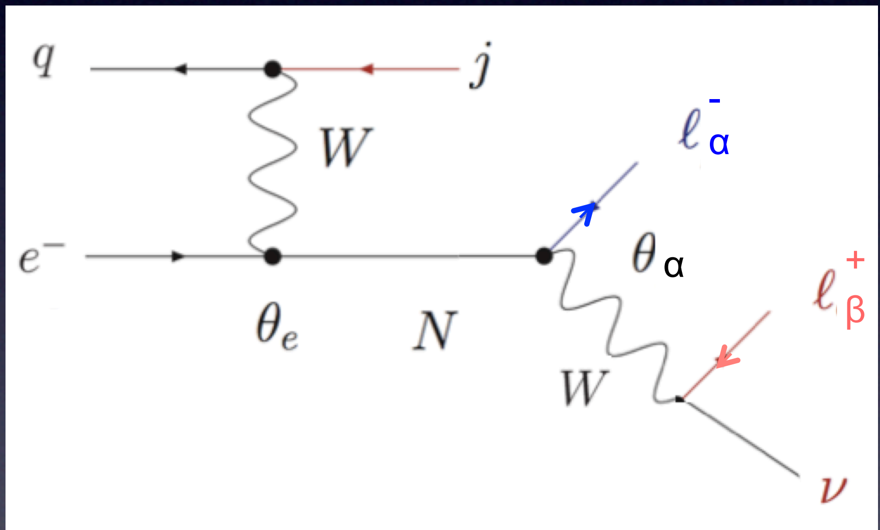
*) Note: Relevant SM background from final states with additional light neutrinos!

Signatures with lepton flavour violation

(at LO)

Different collider types feature different production channels:

Example: Final state at ep colliders (LHeC, FCC-eh): "jet-dilepton"
$j\, l_\alpha^- l_\beta^+ \nu$ with e.g. $\alpha = \tau^-$ and $\beta = \mu^+$



	e^-e^+	pp	e^-p
$\mathbf{W_s}$	×	✓+LNV/LFV	×
$\mathbf{W_t}$	✓	×	✓ +LNV/LFV
$\mathbf{Z_s}$	✓	✓	×
$\mathbf{h}$	(✓)	(✓)	(✓)

Lepton flavour violating LFV (and L number conserving LNC) signatures possible (with no SM background at parton level*). <u>Very promising for future searches!</u>

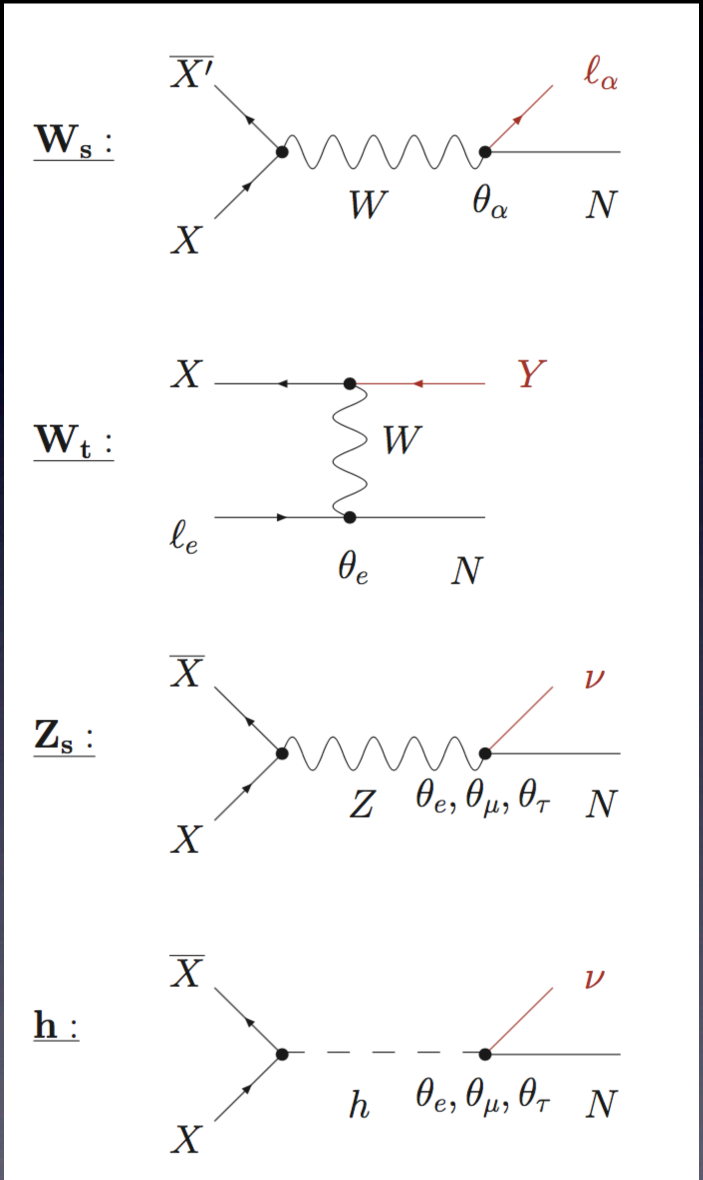
Or e.g.: "lepton-trijet" at ep colliders (LHeC, FCC-eh) l_α^- jjj with e.g. $\alpha = \tau^-$ or μ^-

Or e.g.: "dilepton-dijet" at pp colliders (LHC, FCC-hh) $l_\alpha^- l_\beta^+$ jj with e.g. $\alpha \neq \beta$

*) Note: Relevant SM background from final states with additional light neutrinos!

Signatures for lepton number violation from sterile neutrinos

(at LO)



Different collider types feature different production channels:

	e^-e^+	pp	e^-p
$\mathbf{W_s}$	×	✓ + LNV/LFV	×
$\mathbf{W_t}$	✓	×	✓ +LNV/LFV
$\mathbf{Z_s}$	✓	✓	×
$\mathbf{h}$	(✓)	(✓)	(✓)

<u>Lepton-number violating LNV signatures</u> possible (with no SM background at parton level) <u>but expected to be suppressed</u> by the protective "lepton number"-like symmetry!

However: LNV can get induced by <u>heavy neutrino-antineutrino oscillations!</u>

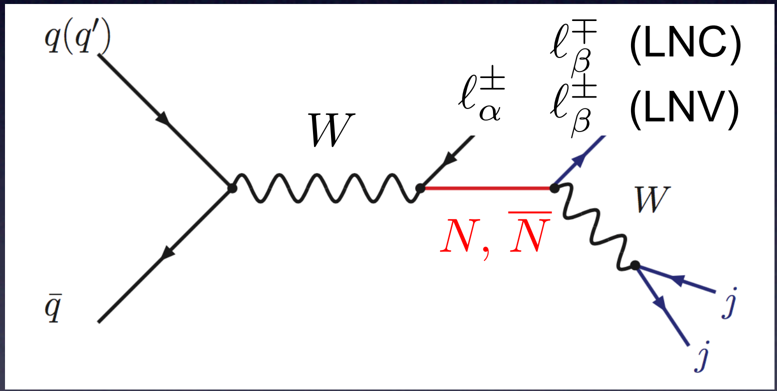
Heavy neutrino-antineutrino oscillations at colliders

Definition: Heavy (anti)neutrino defined via production; superposition of mass eigenstates N_4, N_5

antineutrino, $W^- \to \overline{N}\ell^-$
neutrino, $W^+ \to N\ell^+$

$$\overline{N} = 1/\sqrt{2}(iN_4 + N_5)$$
$$N = 1/\sqrt{2}(-iN_4 + N_5)$$

Consider, e.g., the "dilepton-dijet" signature at pp colliders, pp ➔ $l_\alpha l_\beta$ jj:



In the symmetry limit of the SPSS benchmark model, lepton number is exactly conserved
➔ only LNC process

$pp \to \ell_\alpha^+ \ell_\beta^- jj$ (LNC) ✓
$pp \to \ell_\alpha^\pm \ell_\beta^\pm jj$ (LNV) ×

Heavy neutrino-antineutrino oscillations at colliders

However with perturbations included to generate the light neutrino masses:
Mass splitting ΔM between heavy neutrinos induces oscillations!

Probability that a produced N oscillates into $\bar{N}$ (or vice versa) given by $|g_-(t)|^2$, with

$$g_-(t) \simeq -ie^{-iMt}e^{-\frac{\Gamma}{2}t}\sin\left(\frac{\Delta M}{2}t\right)$$

Mass splitting ΔM predicted e.g. in minimal low scale linear seesaw models

Such an oscillation induces LNV!

Signature: Ratio of LNV/LNC final states oscillates as function of heavy neutrino lifetime (or of vertex displacement in the laboratory system)

$$R_{\ell\ell}(t_1,t_2) = \frac{\int_{t_1}^{t_2}|g_-(t)|^2 dt}{\int_{t_1}^{t_2}|g_+(t)|^2 dt} = \frac{\#(\ell^+\ell^+)+\#(\ell^-\ell^-)}{\#(\ell^+\ell^-)}$$

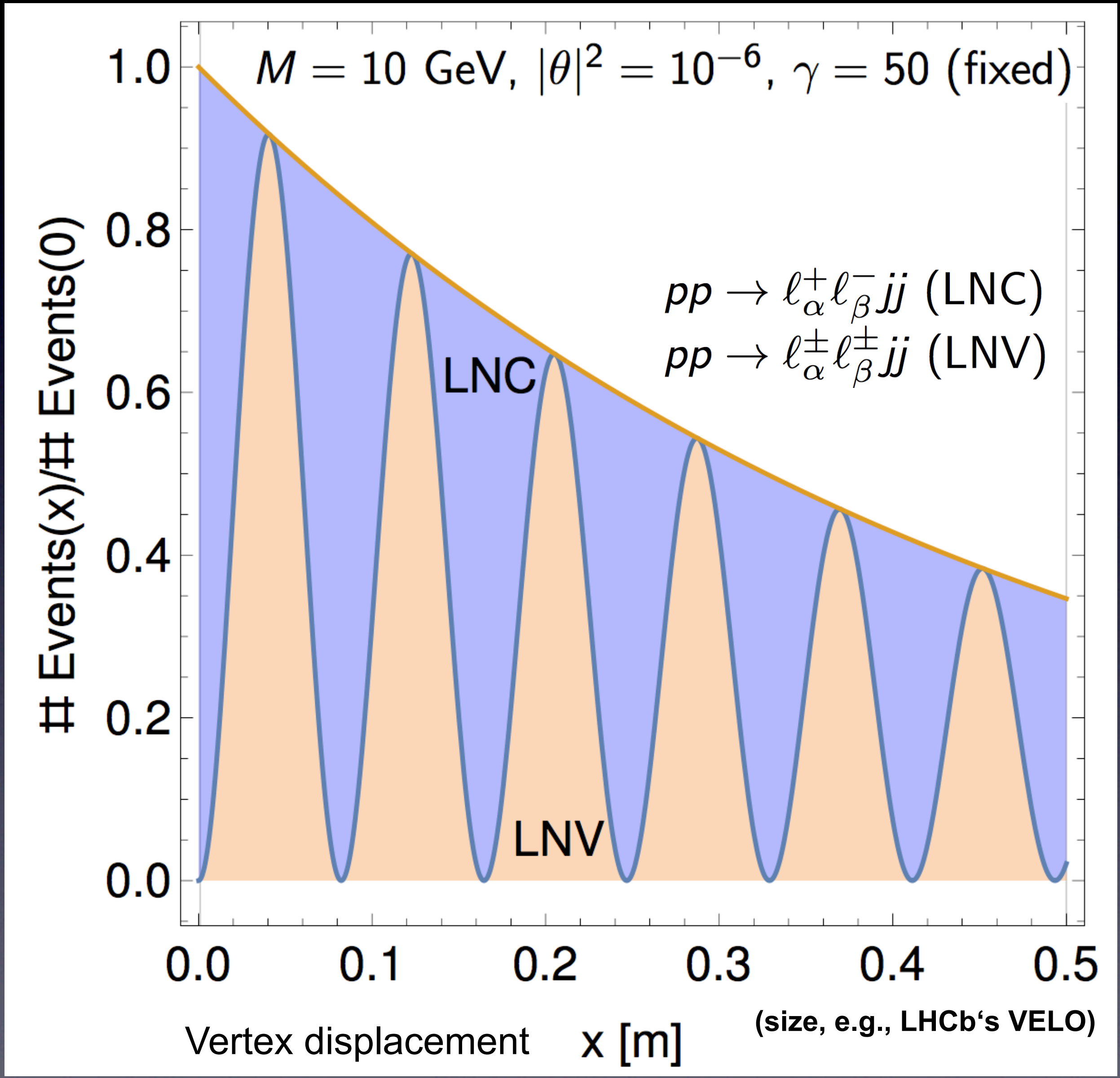
J. Gluza and T. Jelinski (2015), G. Anamiati, M. Hirsch and E. Nardi (2016),
S.A:, E. Cazzato, O. Fischer (2017), A. Das, P. S. B. Dev and R. N. Mohapatra (2017)

With: $g_+(t) \simeq e^{-iMt}e^{-\frac{\Gamma}{2}t}\cos\left(\frac{\Delta M}{2}t\right)$

Recent result: Heavy neutrino-antineutrino oscillations at colliders can be resolvable

Example:
Linear seesaw (inverse mass ordering)

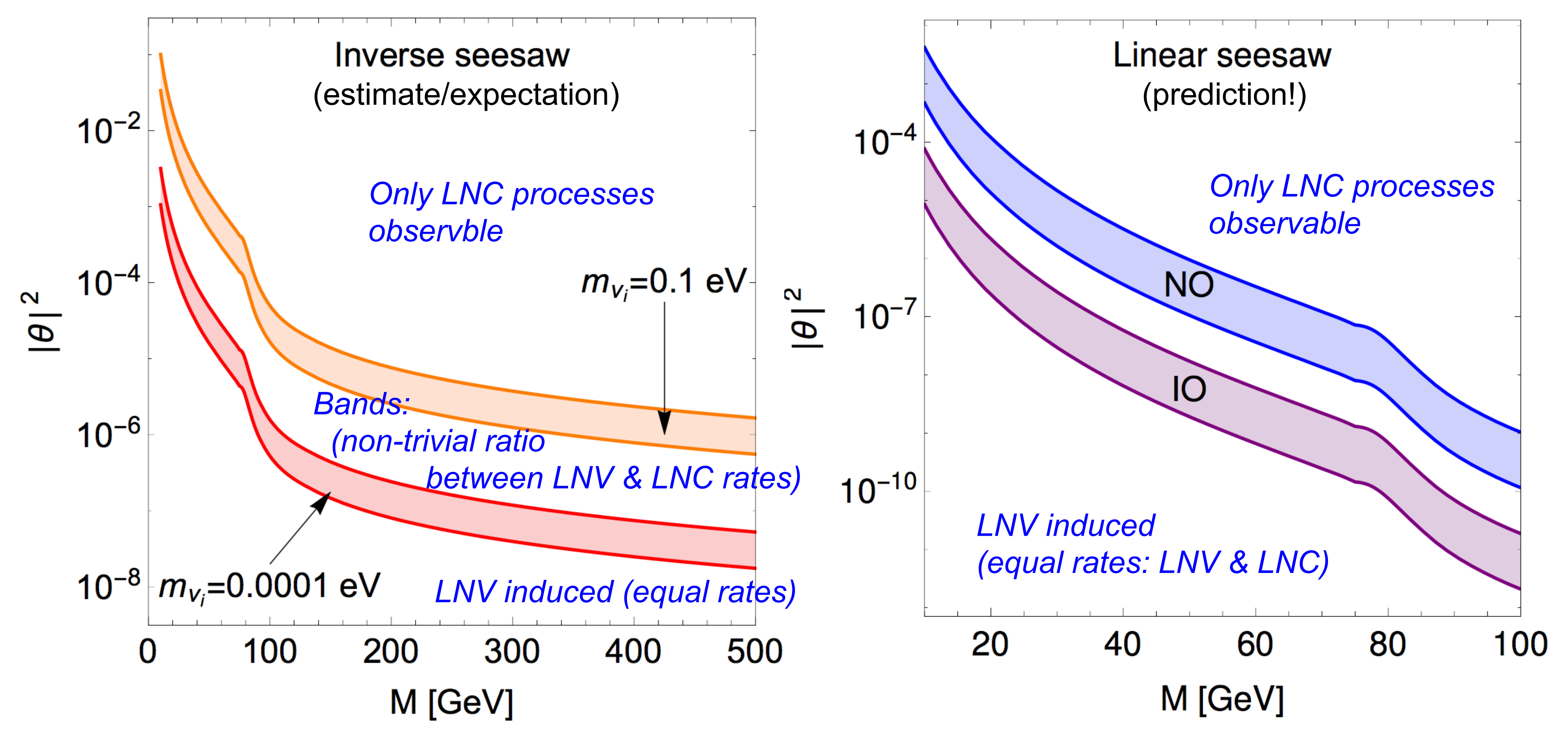
(using the prediction for ΔM in the minimal linear seesaw model for inverse neutrino mass ordering)



S. A., E. Cazzato, O. Fischer (arXiv:1709.03797)

Even if these oscillations are not resolvable, induced LNV can be relevant (depends on θ^2)

Plot from S. A., E. Cazzato, O. Fischer (arXiv:1709.03797)



See also: J. Gluza and T. Jelinski (2015), P. S. Bhupal Dev and R. N. Mohapatra (2015), G. Anamiati, M. Hirsch and E. Nardi, JHEP 1610 (2016),A. Das, P. S. B. Dev and R. N. Mohapatra (2017)

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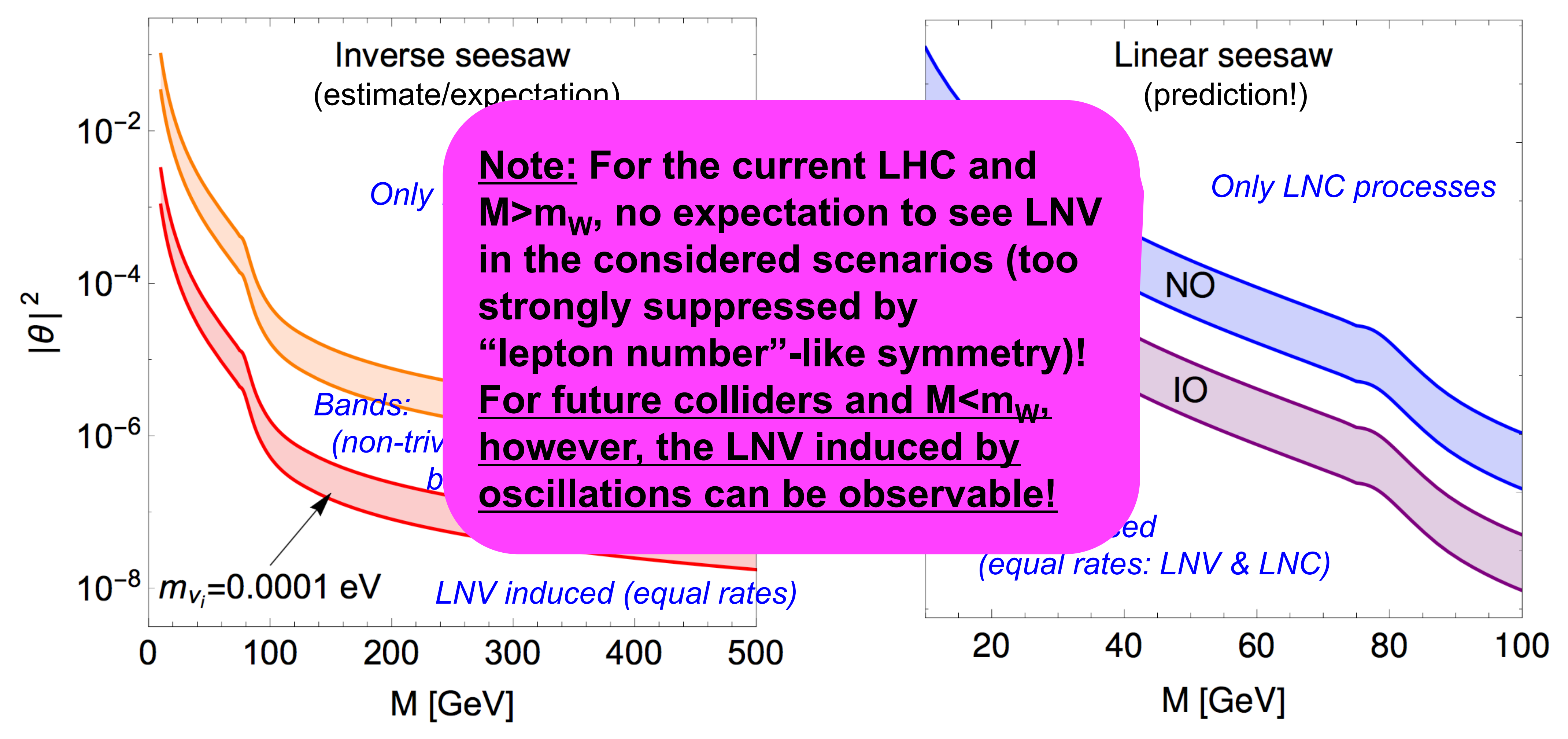
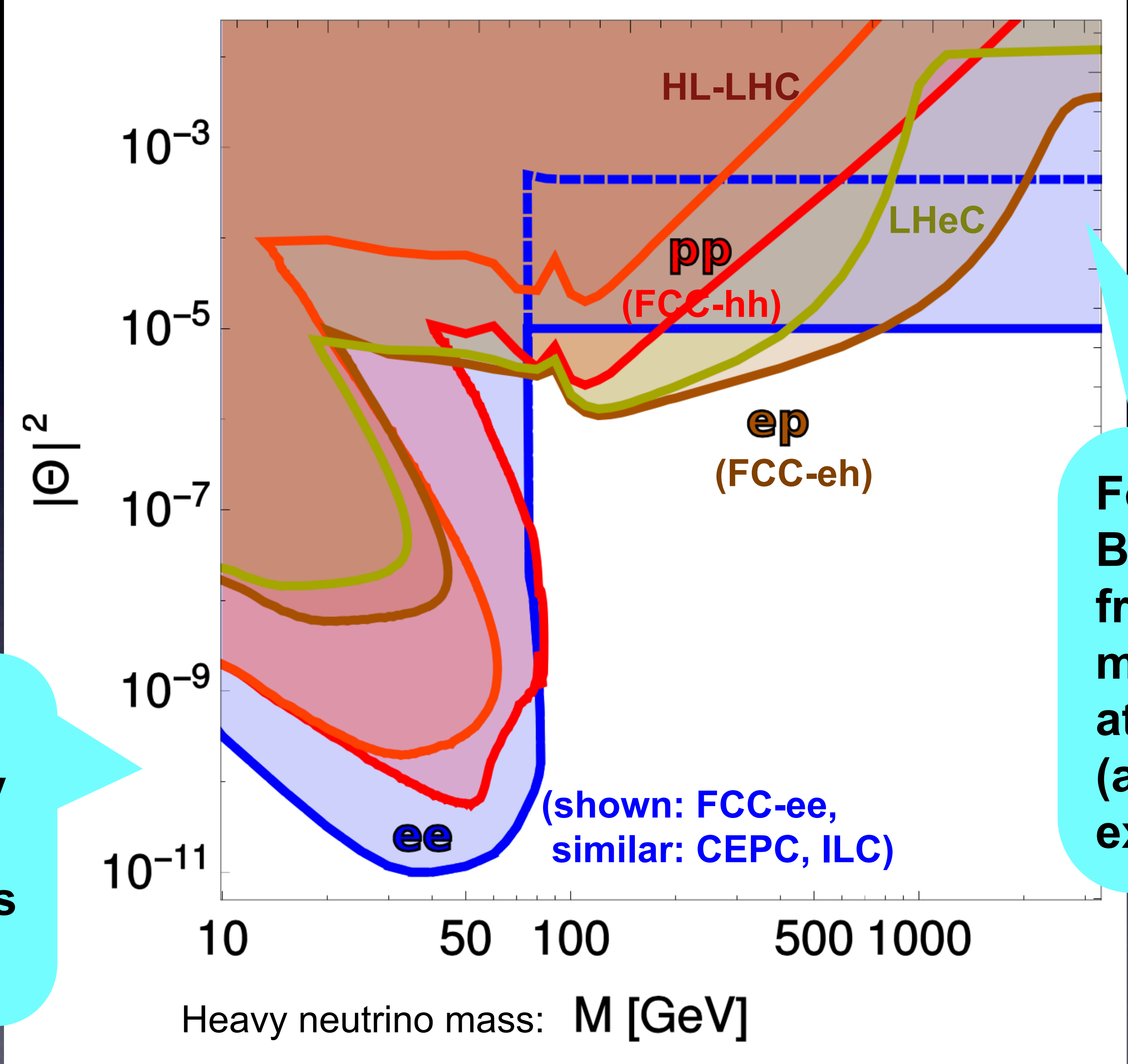


<u>Note:</u> For the current LHC and $M>m_W$, no expectation to see LNV in the considered scenarios (too strongly suppressed by "lepton number"-like symmetry)!
<u>For future colliders and $M<m_W$, however, the LNV induced by oscillations can be observable!</u>

See also: J. Gluza and T. Jelinski (2015), P. S. Bhupal Dev and R. N. Mohapatra (2015), G. Anamiati, M. Hirsch and E. Nardi, JHEP 1610 (2016), A. Das, P. S. B. Dev and R. N. Mohapatra (2017)

Comparison: Estimated sensitivities at future ee, pp and ep colliders

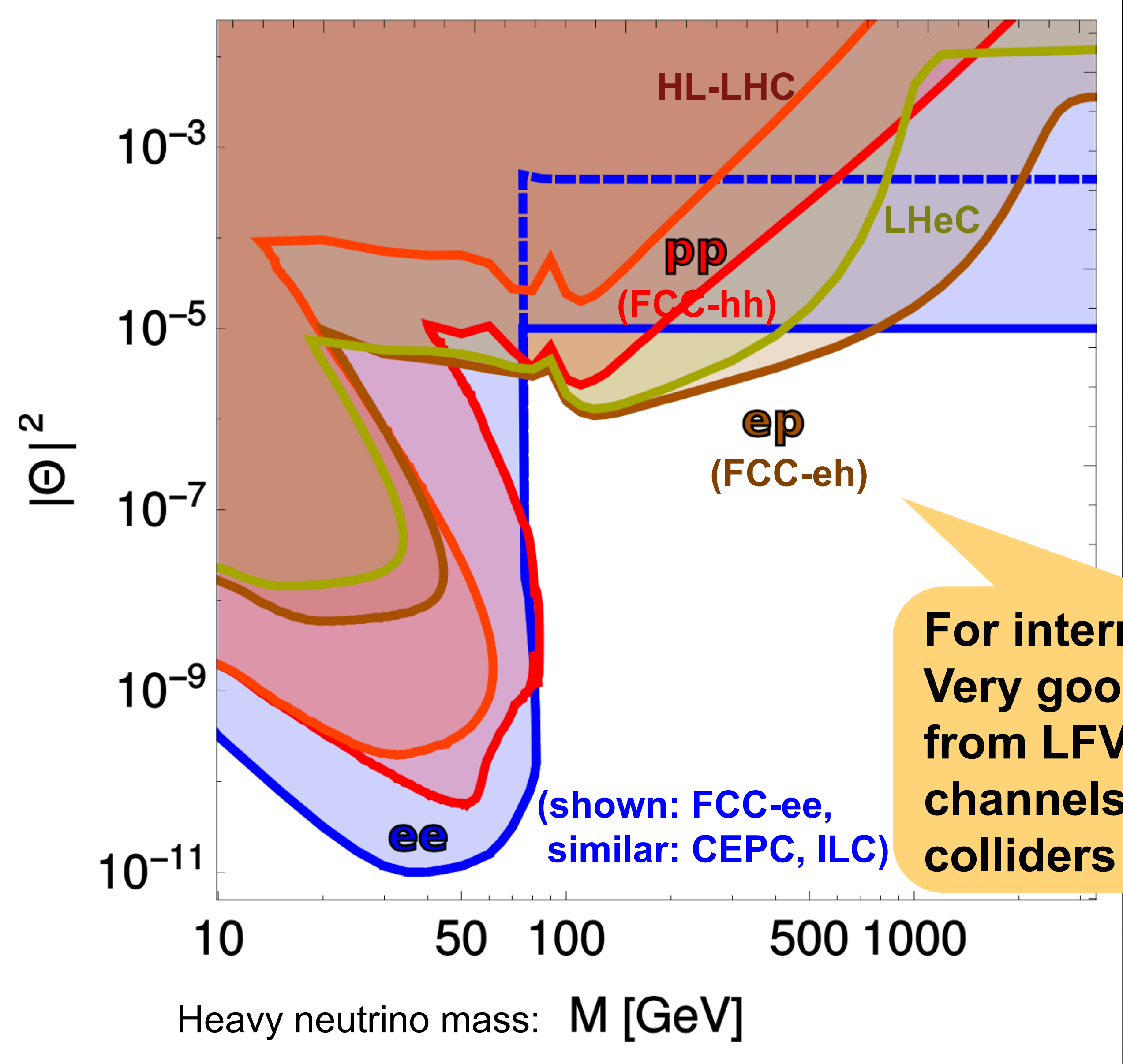


For M < m_W: Best sensitivity from displaced vertex searches at FCC-ee

For M >> O(TeV): Best sensitivity from EWPO measurements at FCC-ee (also: cLFV, see extra slides)

Plot from: S.A., E. Cazzato, O. Fischer (arXiv:1612.02728)

Comparison: Estimated sensitivities at future ee, pp and ep colliders



For intermediate M: Very good sensitivities from LFV (but LNC) channels at pp and ep colliders (FCC-hh & -eh)

Note: Sensitivity to different combinations of active-sterile mixing angles!

Plot from: S.A., E. Cazzato, O. Fischer (arXiv:1612.02728)

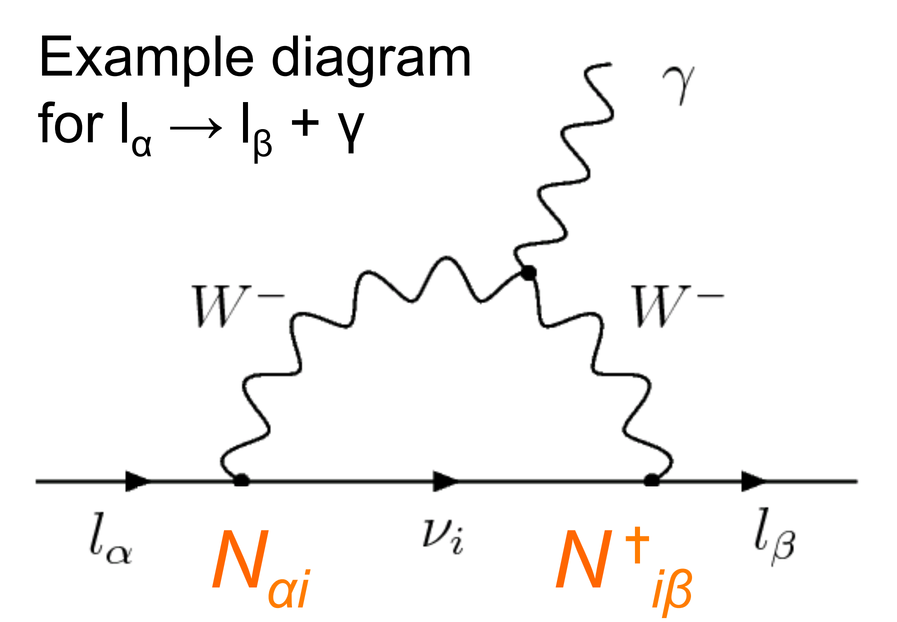
Summary

- Sterile (right-handed) neutrinos are well motivated SM extensions, to explain the masses of the light neutrinos.
- With protective "lepton number"-like symmetry, large y_ν and EW scale M are possible (& technically natural)!
- Using a benchmark scenario (SPSS: Symmetry Protected Seesaw Scenario) we discussed the possible observable effects for EW scale sterile neutrinos.
- Future collider experiments have interesting discovery prospects and, together with neutrino oscillation experiments, have the potential to probe the underlying neutrino mass generation mechanism!

Thanks for your attention!

Extra Slides

Constraints on PMNS Non-Unitarity from cLFV



- Bounds on LFV μ and τ decays $l_i \to l_j\,\gamma$ (and on $\mu \to 3e$ and $\mu \to e$ conversion in nuclei) lead to constraints on the $|\varepsilon_{\alpha\beta}|$:

$$\frac{\Gamma(\ell_\alpha \to \ell_\beta \gamma)}{\Gamma(\ell_\alpha \to \nu_\alpha \ell_\beta \overline{\nu}_\beta)} = \frac{3\alpha}{32\pi} \frac{|\sum_k N_{\alpha k} N^\dagger_{k\beta} F(x_k)|^2}{(NN^\dagger)_{\alpha\alpha}(NN^\dagger)_{\beta\beta}}$$

irrelevant for unitary mixing matrix, but can lead to sizable Br's for non-unitary N!

$$F(x) \equiv \frac{10 - 43x + 78x^2 - 49x^3 + 4x^4 + 18x^3 \ln x}{3(x-1)^4}$$

where:

$$x_k \equiv m_k^2 / M_W^2$$

m_k: light neutrinos' masses

Sensitivites of future cLFV searches to active-sterile neutrino mixing θ_α

- Estimated sensitivities of planned experiments at 90% C.L.:

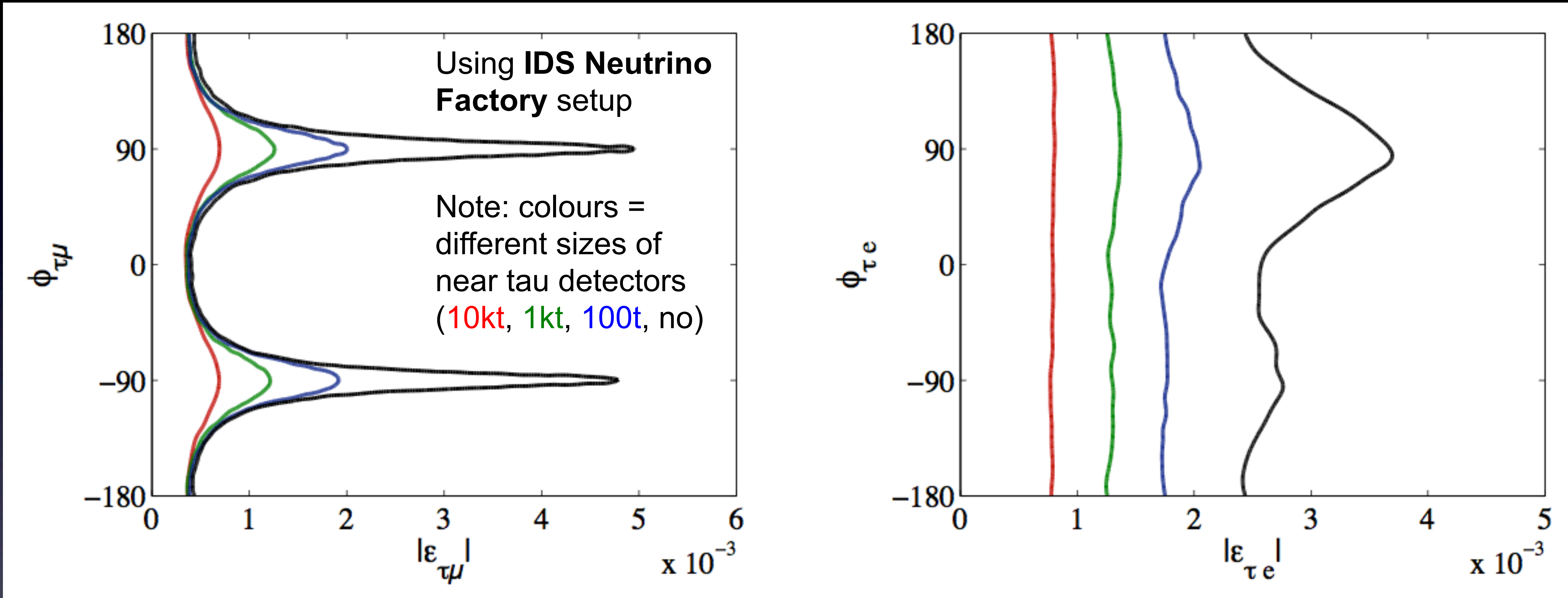
Process	MUV Prediction	Exp. reach	Sensitivity
$Br_{\tau e}$	$4.3 \times 10^{-4} \lvert\varepsilon_{\tau e}\rvert^2$	10^{-9}	$\lvert\varepsilon_{\tau e}\rvert \geq 1.5 \times 10^{-3}$
$Br_{\tau\mu}$	$4.1 \times 10^{-4} \lvert\varepsilon_{\tau\mu}\rvert^2$	10^{-9}	$\lvert\varepsilon_{\tau\mu}\rvert \geq 1.6 \times 10^{-3}$
$Br_{\mu eee}$	$1.8 \times 10^{-5} \lvert\varepsilon_{\mu e}\rvert^2$	10^{-16}	$\lvert\varepsilon_{\mu e}\rvert \geq 2.4 \times 10^{-6}$
$R_{\mu e}^{Ti}$	$1.5 \times 10^{-5} \lvert\varepsilon_{\mu e}\rvert^2$	2×10^{-18}	$\lvert\varepsilon_{\mu e}\rvert \geq 3.6 \times 10^{-7}$

taken from: S.A., O. Fischer (arXiv:1407.6607)

➔ Sensitivity to the products $|\theta^*_\mu \theta_e|$, $|\theta^*_\tau \theta_\mu|$, $|\theta^*_\tau \theta_e|$, due to the relation

$$\varepsilon_{\alpha\beta} = -\frac{v_{\mathrm{EW}}^2 y^*_{\nu_\alpha} y_{\nu_\beta}}{2M^2} = -\theta^*_\alpha \theta_\beta$$

Possible sensitivity of future neutrino oscillation experiments → phases of θ_α



S.A., M. Blennow, E. Fernandez-Martinez, J. Lopez-Pavon (arXiv:0903.3986)

- From the interplay of (tau-sensitive) near and far detectors at, e.g., a neutrino factory, neutrino oscillations could provide information on the phase of the non-unitarity parameters $\varepsilon_{\tau\mu}$ and $\varepsilon_{\tau e}$ (i.e. on the phases of - $\theta_\tau^* \theta_\mu$ and - $\theta_\tau^* \theta_e$)